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Validation and Implementation of Optical Diagnostics for Particle Sizing in Rocket Motors

by

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Lieutenant , United States Navy
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ABSTRACT

Aluminum oxide(Al_2O_3) particles of known size distribution were cast into a solid propellant which burned at temperatures less than the melting point of Al_2O_3. Thus, particles of known size distribution existed at the nozzle inlet and in the plume. Malvern particle sizing instruments were used to make measurements at these two location using a windowed subscale motor and the results were compared to the known distribution. In the motor, measurements were limited due to disruptive flow from the window purge gas. However, the unaffected larger modes were properly measured. In the plume, the measurements of the modes were quite accurate, but low signal strength resulted in some inaccuracies for the mass contained in each mode. A phase Doppler particle analyzer was adapted to an existing plume probe. Initial measurements at two radial locations were in good agreement with the expected size distribution.

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I. INTRODUCTION

Metals are commonly added to solid rocket motor propellants to increase the specific impulse(I_{sp}) over the base propellant by adding energy to the combustion process. Metals are also added to increase the stability of the combustion by suppressing the transverse modes of oscillation (higher frequencies). The most commonly added metal is aluminum because of its high heat of combustion, low cost, and availability [ref. 1]. When aluminum is added to a solid propellant, there are associated problems such as primary smoke, two-phase flow losses and nozzle erosion [ref 2,3]. Two-phase flow losses are associated with lags in velocity and temperature between the condensed (Al_2O_3) particles and expanding gases and they are usually the greatest factor in determining nozzle efficiency.

There is an ongoing study of condensed aluminum oxide particle behavior in the chamber, across the exhaust nozzle and in the plume of solid rocket motors at the Naval Postgraduate School(NPS). Diagnostic techniques are directed at obtaining particle size distributions and the plume IR and visible signatures. To date, particle size measurements have been made using ensemble and single particle forward scattering of laser light, combined collection/optical probes and collection of particles on impact probes. Collected particles are analyzed using a scanning electron microscope(SEM). IR measurements are made using both a thermal imaging camera and a spectroradiometer.

Although good agreement has been obtained between the various

particle sizing techniques employed, questions have been raised as to the accuracy of the measurements. One of the purposes of this investigation was to validate the ensemble particle sizing technique using an approach similar to that of Traineau,et,al [ref 4]. Control propellants, or propellants with known size distributions of aluminum oxide, are burned in a subscale motor. The combustion temperature of the propellants are kept below (through ingredient tailoring) the melting temperature of Al_2O_3 (2318K). Thus, the particle size distributions measured at the nozzle entrance and exit should be the same as that cast into the propellants.

A combined optical/collection probe has also been developed at NPS[ref 5,6] which permits localized plume sampling. It was designed to be used with a Malvern Mastersizer[ref 7]. This instrument is an ensemble particle analyzer and measurement is based upon the intensity profile of forward scattered light. Contamination of the optical windows was a continuing problem with the original design. In an attempt to overcome the limitation, a phase Doppler particle analyzer(PDPA) has recently been acquired. This device is a single particle analyzer in which the measurements are based upon phase-shift rather than intensity of the scattered light. Thus, the measurements should be less sensitive to probe window contamination. Another advantage of the PDPA over the Malvern for this application is that the instrument can be located more remote from the probe, decreasing disturbances to the plume flow field. The second purpose of this investigation was to adopt

the probe to the PDPA instrument and to demonstrate its capabilities by making plume measurements.

II. EQUIPMENT

A. **SUBSCALE MOTOR**

An axisymetric motor was used for the collection of data. The chamber(internal) diameter was 5.1 cm. The length was 25.4 cm with a residence time of 30 - 50 ms. The motor used viewing windows for collection of data in the motor chamber. It was modified with an additional window, offset by 50° to accommodate the PDPA measurements. To prevent excessive contamination of the viewing windows, a nitrogen purge system was included for each window. The flow rate of the nitrogen purge was approximately 10% of the propellant mass flow rate. The end-burning propellant grain was 5.1 cm in diameter and 2.54 cm thick. The exhaust nozzle was made of copper, had a converging half-angle of 45° and throat diameter of 0.5 cm.

B. **PROPELLANTS**

All propellants were provided by the Air Force Phillips Lab, Edwards AFB, California.

1. Calibration Propellants

These propellants were to be used for validation of the Malvern particle sizers for obtaining particle size distributions in the motor and plume.

TABLE I. PROPELLANT 1 COMPOSITION

PROPELLANT CONSTITUENTS	COMPOSITION	WEIGHT PERCENT
Aluminum Oxide	Al_2O_3	16%
Ammonium Perchlorate	NH_4ClO_4	32%
Ammonium Nitrate	NH_4NO_3	21.9%
GAP	$C_3H_5N_3O$	26.7%
IPDI	$C_{12}H_{18}N_2O_2$	3.2%
Others		0.2%

There were three specially formulated propellants(Table I) that differed only by the size distributions of the aluminum oxide(Table II). The various size distributions were selected to represent those that had been previously measured or predicted to occur at the nozzle inlet and exit. Spherical Al_2O_3 was not available. The specific sizes were provided by the manufacturer. The irregular shapes of Al_2O_3 can be seen in the SEM pictures in Figs 1-4. The propellant combustion temperature(2076K[1]) was kept lower than the melting point of aluminum oxide(2318K) for a 450 psia combustion chamber pressure.

[1]The temperature value was computed with the Micropep program[ref 8].

TABLE II. SIZE DISTRIBUTIONS OF AL_2O_3

1A	1B	1C
10% 2 micron 70% 5 micron 20% 20 micron	65% 2 micron 35% 122 micron	20% 2 micron 80% 122 micron

2. Propellant 2

This propellant [Table III] was used to provide spherical Al_2O_3 particles at the entrance of the exhaust nozzle and in the plume. Firings were made in which the PDPA was used in the motor or with the probe in the plume.

TABLE III. PROPELLANT 2 COMPOSITION

PROPELLANT CONSTITUENTS	COMPOSITION	WEIGHT PERCENT
Aluminum (5-20 MICRONS)	Al	4.68%
Ammonium Perclorate	NH_4ClO_4	70.31%
GAP	$C_3H_5N_3O$	14.67%
TEGDN	$C_6H_{12}N_2O_8$	8.49%
Others		1.84%

The density of the propellant was 1.76 g/cc.

C. **MALVERN 2600HSD**

The 2600HSD[ref 9] measures forward scattered light with a maximum angle of 14°. The system has a transmitter and receiver.

The transmitter provided a 2 mW helium neon laser beam (633 nm wavelength) expanded to 9 mm. The receiver can detect a size range of .5 to 564 microns, broken up into three ranges that are determined by the choice of the receiver lens (63 mm, 100 mm, 300 mm). These Fourier transfer lenses focus the scattered light onto 31 concentric diodes and the data are processed using Fraunhofer diffraction theory. The read time for one sweep of the diode array is approximately eight milliseconds. This investigation used the 100 mm lens with a detection range of 1.9 to 188 microns and vignetting distance of 133 mm. The volume of particles in the range 0.5 to 1.9 microns is also estimated by the Malvern software.

D. **MALVERN MASTERSIZER**

The Mastersizer[ref 7] also measures forward scattered light, but to a maximum angle of approximately 50°. The transmitter provided a 2 mW helium-neon laser beam expanded to 18 cm. The receiver can detect particles with diameters from 0.1 to 600 microns depending on the focal length of the receiver lens(45 mm,100 mm,300 mm). The 45 mm lens uses reverse Fourier optics while the 100 mm and 300 mm lens use conventional Fourier optics. The processing of the scattered light data uses Mie corrections to Fraunhofer diffraction for smaller particles. The experiment used a 100 mm lens with range of 0.5 to 180 microns and a vignetting distance of 29 mm.

E. AEROMETRICS PHASE DOPPLER PARTICLE ANALYZER

The PDPA utilizes an argon ion laser with 2 watts of power at 514.5 nm[ref 10]. The transmitter splits the beam into two beams of equal intensity, 20 mm apart. One beam is an unshifted, zero order beam. The second beam is a first-order beam shifted by 40 MHz. The beams are crossed at a lens focal length of 250 mm to form the probe volume. As a particle moves through the probe volume, light is scattered. The doppler signal analyzer uses high speed analog-to-digital converters to record the signal. The analyzer uses a fast Fourier transform to determine the frequencies of the signal. It is capable of measuring particle sizes as small as 0.5 microns(with a dynamic range of 50:1). It can measure greater than 300,000 particles/sec with velocities up to 1900 m/s, depending upon the selected focal lengths of the transmitter and receiver lenses.

The PDPA measurement is based upon the phase-shift of scattered light from a particle. Geometric optics are assumed to apply, in which the scattered light consists of reflection, refraction, 2nd order refraction and diffraction. For a specific index of refraction, plots are made of scattered power vs. scattering angles(0-180°) for each of the individual types of scattering and the total(Mie) scattering. Angles are chosen where one type of scattering (reflection or refraction) dominates. Then the phase shift at multiple detectors produced by a particle as it passes through the crossed-beam probe volume is plotted against particle diameter for the chosen type of scattering and scattering angle. This plot turns out to be linear for non-absorbing particles, when

forward scattering measurements of refracted light are made(typically ~50°). The same is true for highly absorbing particles when reflected light is measured in the backscattering mode.

Aluminum oxide is slightly absorbing and the index of refraction and absorption index vary considerably with particle temperature, particle size and the degree of contamination(soot, aluminum, etc). A "best" estimate for the plume particles index is $m = 1.74-i(3x10^{-5})$. Unfortunately, the low absorption index results in some non-linearity in the phase-shift vs. diameter correlation for backscattering, when particles are smaller than 40 microns. The software uses a linear correlation, so uncertainties in m can be translated to uncertainties in diameter. The more accurately m is known, the more accurately the diameter can be measured. In this experiment, a 50° backscattering angle was used.

F. **PROBE**

The dimensions of the probe are shown in Fig 5. The object of the probe is to isolate a small stream of the particles in the exhaust flow [ref 5,6]. The probe tip is designed to swallow the strong normal shock that could break up particles. Weaker oblique shocks form inside the probe tip. The window is large enough to allow for the incoming light source as well as the back-scattered light of the PDPA. Figure 6 shows the probe attachment which was designed and fabricated to protect the PDPA from exhaust products outside the probe. The probe initially had a nitrogen purge system

to keep the window relatively free of particles, but also to prevent recirculation of the particle as they exit the tip and pass into the probe chamber.

III. EXPERIMENTAL PROCEDURES

A. **MALVERN VALIDATION**

Spherical aluminum oxide particles were not available; instead, non-spherical aluminum oxide particles in four size distributions were used. The software used by the Malvern particle sizers assumes that particles are spherical. Therefore, calibration data were required to determine the "equivalent" spherical particle size distributions for the aluminum oxide cast into the propellants.

Individual particle size distributions were suspended in solution and data were collected using the Malvern particle sizers. Multi-modal size distributions were then prepared by first collecting data on individual size distributions and determining the volume concentrations of particles (V_P) with the following equation:

$$\%CONC=\frac{(V_P)}{(V_L)}$$

The percentage of particles in liquid (%CONC) was obtained from the Malvern particle sizer output and the volume of liquid (V_L) was measured with a disposable pipette. After determination of the first particle size distribution and volume(V_P), and knowing the desired percentage of the particle size distribution in the multi-modal size distribution, the required %CONC for the other size distributions could be calculated. The individual particle size distributions were mixed to less than 5% error of the required %CONC. The individual size distributions were then mixed together

and multi-modal data were collected by the Malvern particle sizers.

Multi-modal size distributions were measured at the nozzle entrance and exit[Fig. 7] during motor firings for comparison with the calibration data in order to access the accuracy of the Malvern measurements in the rocket motor enviroment.

B. PDPA

The PDPA transmitter was arranged perpendicular to the probe/motor and the crossed-beam volume was parallel to the particle flow to acquire velocity and size distribution data. The receiver was placed above the transmitter at a 50° backscatter angle. The laser was directed through a beam waist adjuster and polarization rotator before being adjusted through three steering mirrors[Fig. 8] and passed into the transmitter. The system was aligned before each test.

1. Measurement in the Plume

The PDPA was used in conjunction with the combined collection/optical probe. The particle size distribution was measured on the centerline of the plume at 13.5 nozzle exit diameters(13.5cm) downstream of the nozzle. Then, the particle size distribution was measured at 13.5 nozzle exit diameters downstream, but radially displaced by 1.3 cm (1.3 nozzle exit diameters). The data were compared to data obtain in another investigation which utilized the Malvern particle sizer.

Severe window contamination remained a problem. Therefore to permit longer data acquisition times, the windows were removed from the probe and protective windows were instead placed over the lenses of the receiver and transmitter. This also allowed the window purge system to be eliminated. Only a small ejector nozzle flow was required in the probe.

2. Measurements in the Motor

The modified window as well as the existing window restricted the width of the transmitted beams and reflected light. This allowed measured size distributions at 0.65R from the motor centerline, where R is the internal radius of the motor. Since the grain was an end-burner, the collected data should not be effected by the probe volume location because the size distribution is approximately constant throughout the motor.

IV. RESULTS

A. MALVERN MEASUREMENTS WITH CONTROL PROPELLANTS

1. Calibration

The 122 micron diameter particles were too heavy to suspend in distilled water. The use of a heavy liquid with a density of 2.45 was attempted. Problems were then encountered trying to suspend particles from the 2 microns size distribution. These particles could not be efficiently distributed in the heavy liquid. Other methods were attempted, but no reliable data were obtained. Accurate calibration data were only collected for the 2,5, and 20 micron tri-modal size distribution and, therefore, the only propellant that was fired in the motor contained this mixture of Al_2O_3.

For the 2600HSD, individual size distributions (2,5,20) were multiplied by the percentage each had in the tri-modal distribution(8,65,27% respectively). These adjusted individual distributions are plotted[Fig. 9a] along with the sum of the distributions(e.g., the expected distribution for the tri-modal mix). The "expected" tri-modal distribution is plotted with the measured tri-modal distribution in Figure 10. There was good agreement. The small differences could be attributed to the process used when the 2 and 20 micron distributions were transferred from their optical vials to the optical vial that contained the 5 micron distribution.

The same procedure was repeated for the Mastersizer[Figs. 11b and 12]. The results were again in good agreement. Comparison between the results obtained with the two Malvern particle sizers for obscuration(OBS), Sauter Mean Diameter(D_{32}) and mode are shown in Table IV.

TABLE IV. CALIBRATION DATA

SIZE DISTRIBUTION	OBS	D_{32} (MICRONS)	Mode (MICRONS)	% V_P in the tri-modal
2 MICRON MS 2600	0.31 0.42	4.9 4.5	6.4 6.3	9 8
5 MICRON MS 2600	0.40 0.54	7.8 7.7	9.4 10.6	73 65
20 MICRON MS 2600	0.15 0.29	21.1 24.9	24.3 29.8	18 27
TRI-MODAL MS 2600	0.38 0.48	7.9 8.6	9.4 6.8, 11.4, 32.0	

2. Motor firing data

Since the calibrations for the 2600HSD and Mastersizer were in good agreement and only limited propellant was available, the motor firing data were collected only with the Malvern 2600HSD.

a. Measurements in the Motor

As the particles pass through the beam volume, light is scattered in the forward direction at various angles. Smaller particles scatter more light at larger angles. The window cavity in the motor restricted the detector field of view. Therefore smaller particles must pass closer to the window cavity than larger

particles in order to prevent vignetting. Thus the motor geometry introduced some bias into the measurement process. For this experimental set-up, there was no bias for particles greater than 5 microns.

The expected tri-modal distribution for the propellant composition is shown in figure 13. Also shown is the "expected" tri-modal distribution with the window vignetting effect taken into consideration. It can be seen that vignetting had little effect on the "expected" distribution.

The measured distribution is also shown in figure 12. No particles were measured below 10 microns. This could have resulted from a motor plug that inadvertanlly vented during the run, just above the windows. Small particles may have followed the vented gas. Another possibility was that the window purge system pushed the smaller particles out of the beam volume, effectively preventing detection. The propellant had a very low burn rate, resulting in a chamber pressure(P_c) of approximately 200 psia(including the mass flow from the window purge system. The low propellant burning rate resulted in the window purge flow velocity being approximately equal to the gas velocity in the chamber. This problem of detecting no small particles was also evident in the motor run which used the PDPA. No particles passed through the crossed-beam volume located near the wall just outside of the window cavity. The mass of aluminum oxide contained in the propellant which had diameters less than 10 microns was approximately 38%. Assuming that these particles were not in the

measurement volume would result in a different "expected" distribution as shown in figure 13. It is seen that the two large modes were identified, though shifted toward each other.

It is apparent that a method needs to be found which greatly reduces or eliminates the window purge flow rate.

b. Measurements in the Plume.

Without window purge gases added in the chamber, this low burning rate propellant produced chamber pressures of only approximately 100 psia. This resulted in a very low mass flow rate, which translated into very weak light scattering signals from the particles in the plume. In the future, the mass flow rate should be increased, by reducing the diameter of the nozzle throat. However, this may cause problems with clogging of the throat due to the 16% aluminum oxide in the propellant.

Figure 13 compares the measured particle size distribution with the distribution in the propellant. All the modes were correctly measured as were the relative masses in the two smaller modes. However, the smallest particles were not detected. The measured mass in the largest mode was too high. Very small changes in the recorded intensity at small angles were observed to significantly change the measured distribution. Future tests should eliminate the laser line filter used in the front of the receiver to increase the signal strength. This coupled with higher propellant flow rates should eliminate the problem.

B. **PDPA MEASUREMENTS**

1. Measurements in the Plume

Three samples were taken with the PDPA/probe. Figures 14 and 15 are examples of the data output by the PDPA. The number of valid samples compared to the number of attempted measurements was very low. The Phase Doppler Analyzer has size and velocity limits for a given size of transmitter and receiver lens. Every particle that passed through the crossed-beam volume was recorded as an attempt. The Phase Doppler analyzer was designed with the ability to go back and review the recorded "buffer data". This was done in an attempt to determine the cause for the large number of rejections. It appeared that many(perhaps 50%) of the rejections resulted from particles smaller than 0.7 microns.

The data collected from the three runs showed a decrease in the number of larger particles as the probe was moved radially outward in the plume[Table V and Figs. 15 and 16]. This was

TABLE V. PDPA/PROBE DATA

PDPA				
RUN	LOCATION	D_{32} (microns)	V_{ave} (m/s)	Mode (microns)
1	centerline	18.8	227	32
2	centerline	17.9	209	28
3	radially spaced (1.3 ex. dia)	9.7	105	30
MALVERN				
1	across plume	1.3		28

expected since larger particles have been predicted and measured to

be concentrated along the plume centerline as a result of not being able to turn rapidly with the gases through the nozzle throat. The data from the Malvern[Ref. 11, Fig. 17] was obtained including all particles across the width of the plume and resulted in a D_{32} of 1.3 microns. That measurement included the dominantly small(< 2.0 microns) particles in the outer plume region. The plume volume outside of the radius where the PDPA measurements were made was approximately 2.5 times as large as the region measured. The initial PDPA/probe results look quite realistic. Future measurements should be made at various radial locations for direct correlation with the Malvern data.

2. Measurements in the Motor

No valid data were obtained in the motor. As discussed above, it is believed that the high window purge velocity(relative to the low combustion flow velocity from the low burning rate propellant) removed all the particles from the near-wall probe volume location.

V. CONCLUSIONS AND RECOMMENDATIONS

Measurements made with the Malvern particle sizers were in good agreement with each other and the both were effective in correctly locating the modes of multi-modal distributions.

The Malvern and PDPA measurements made in the motor revealed a problem with the method of keeping the windows clean. Unless high propellant flow rates(pressure) are used, the window purge flow significantly disrupts the combustor flow, removing most particles near the wall and biasing the measurements toward the larger particles in the rest of the measurement volume. Within these hardware limitations, the Malvern measurements correctly located the modes of the distribution.

Malvern measurements in the plume accurately located the modes of the tri-modal distributions of the aluminum oxide in the control propellant. Low propellant flow rates resulted in low scattered light intensity in the plume. This apparently made the measured mass-in-mode very sensitive to small changes in the recorded intensity profile.

The PDPA was successfully adapted to the combined optical/collection probe and initial measurements were in agreement with the expected plume particle size distribution.

It is apparent that a better method is needed for motor measurements. The motor must eliminate the window purge system, but still reduce severe window contamination.

The PDPA/probe work should be continued in various locations

of the plume. In addition, a multiple-wavelength extinction measurement system should be incorporated in an attempt to measure the particles which are smaller than 0.5 microns.

VI. APPENDIX A: FIGURES

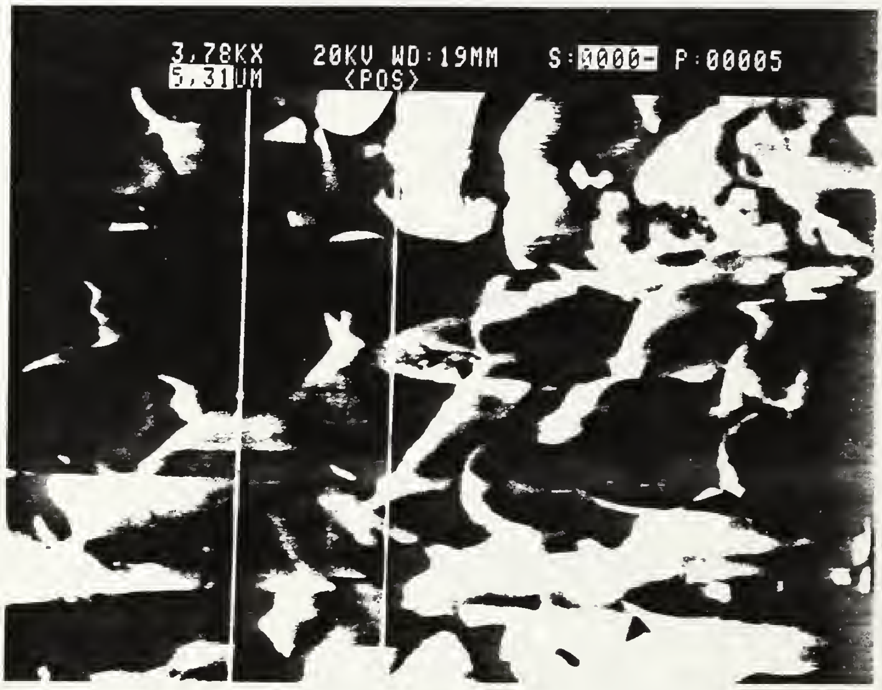


FIGURE 1: 2 MICRON Al_2O_3

FIGURE 2: 5 Micron Al_2O_3

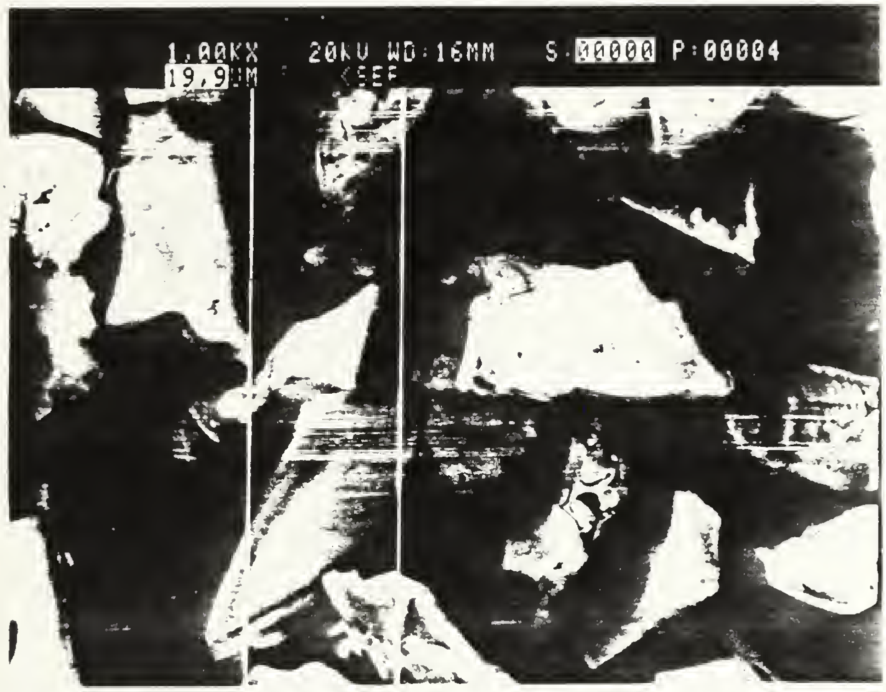


FIGURE 3: 20 Micron Al_2O_3

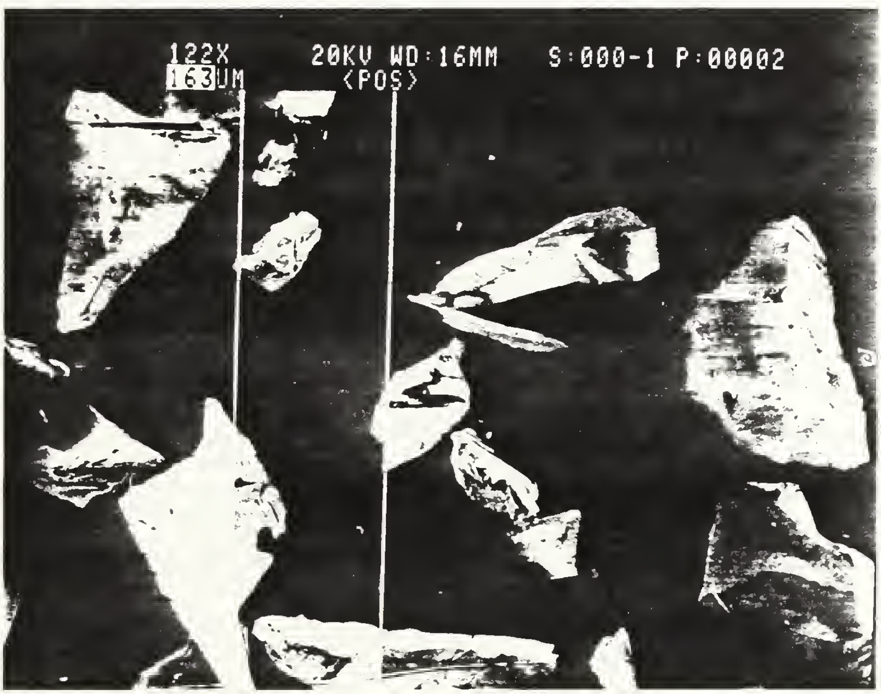


FIGURE 4: 122 Micron Al_2O_3

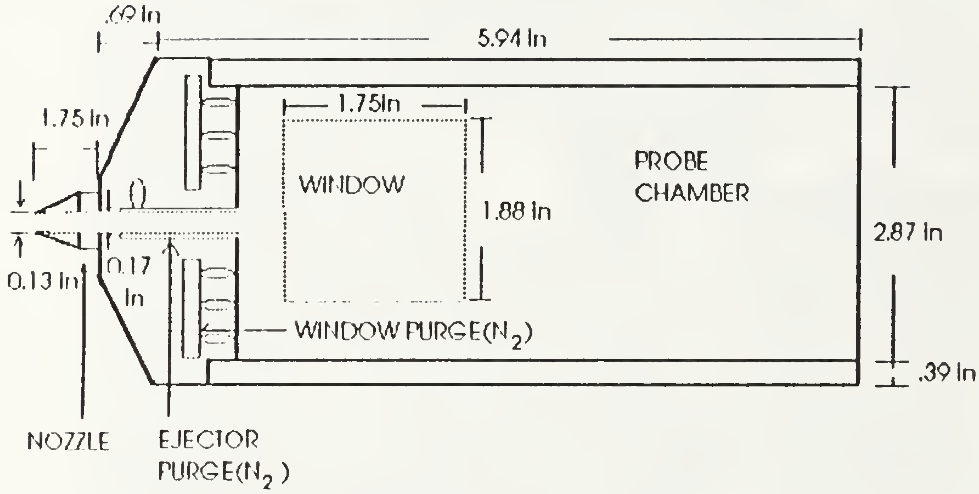


FIGURE 5: The Probe

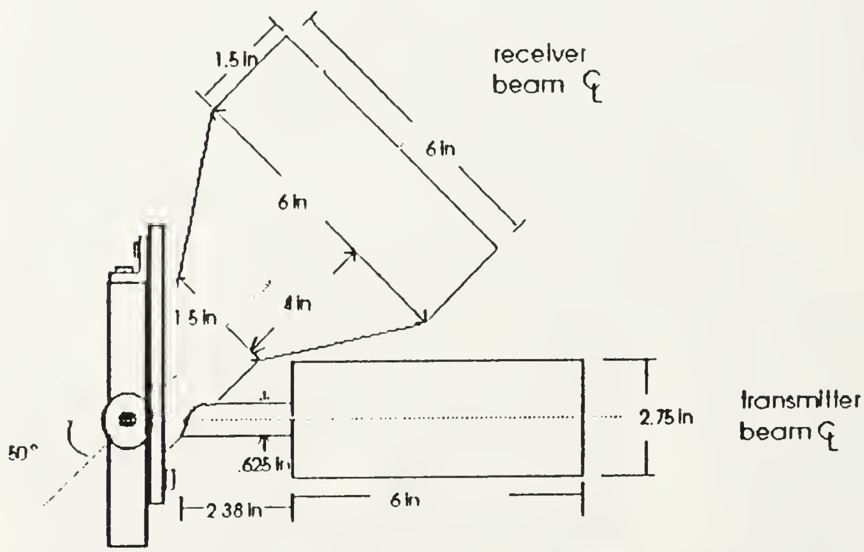


FIGURE 6: Probe Attachment

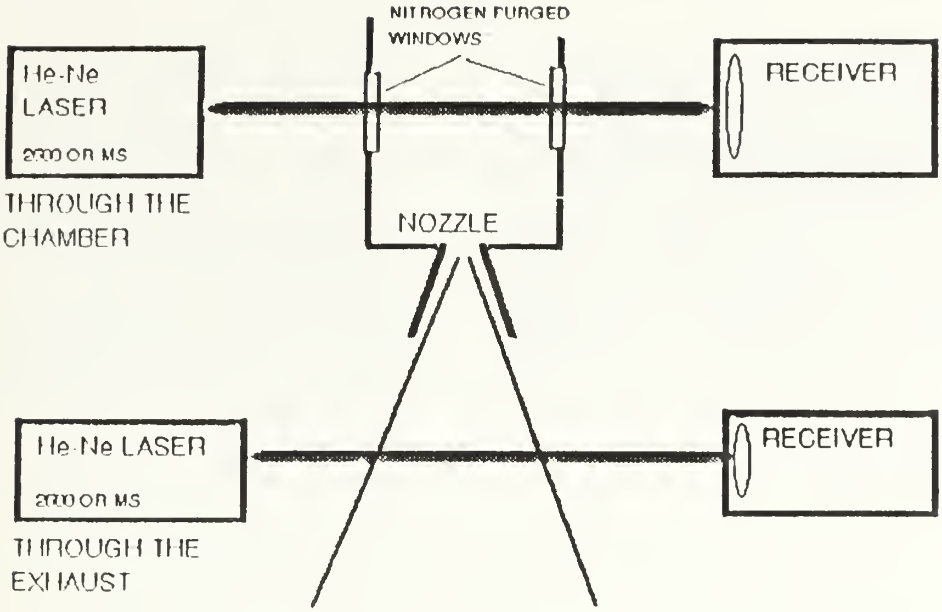


FIGURE 7: Malvern Set-up

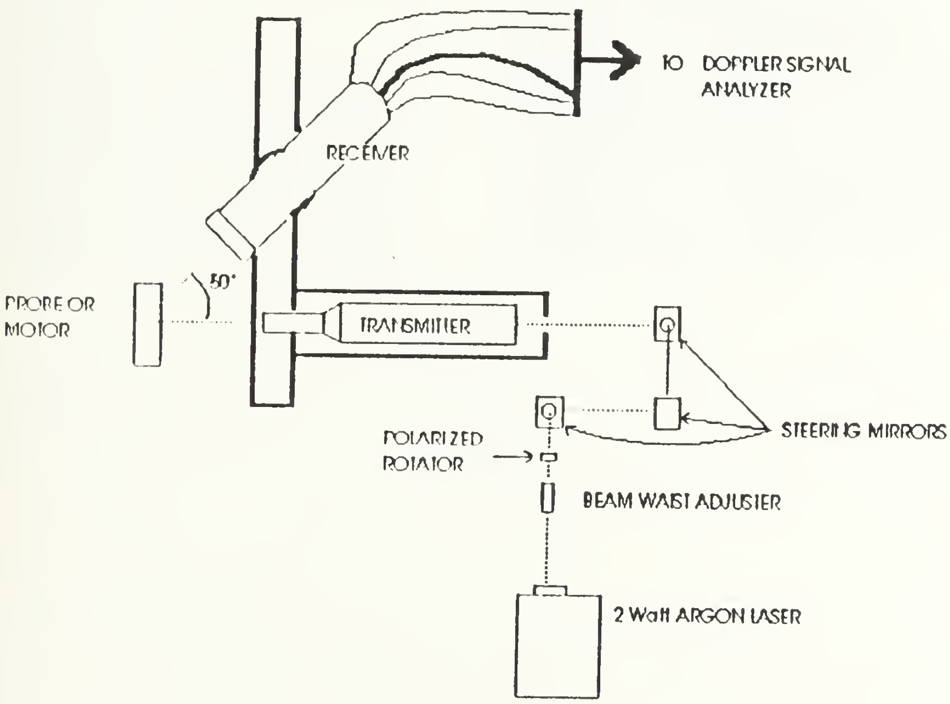


FIGURE 8: PDPA Set-up

Upper	In	Lower	Under	Upper	In	Lower	Under	Upper	In	Lower	Under
				57.7	0.0	49.8	100	9.82	6.2	8.47	82.1
				49.8	0.0	43.0	100	8.47	10.4	7.30	71.7
				43.0	0.0	37.0	100	7.30	14.7	6.30	57.0
				37.0	0.0	32.0	100	6.30	14.7	5.43	42.3
188	0.0	162	100	32.0	0.0	27.5	100	5.43	11.5	4.68	30.8
162	0.0	140	100	27.5	0.0	23.8	100	4.68	7.4	4.05	23.4
140	0.0	121	100	23.8	0.0	20.5	100	4.05	6.2	3.48	17.2
121	0.0	104	100	20.5	0.0	17.7	100	3.48	5.2	3.02	12.0
104	0.0	89.8	100	17.7	0.0	15.3	100	3.02	3.6	2.60	8.4
89.8	0.0	77.5	100	15.3	0.5	13.2	99.5	2.60	2.6	2.23	5.9
77.5	0.0	66.8	100	13.2	4.9	11.4	94.6	2.23	2.0	1.93	3.9
66.8	0.0	57.7	100	11.4	6.3	9.82	88.3	1.93	3.9	0.50	0.0

Span 1.26
D[4,3] 6.12µm
D[3,2] 4.51µm
D[v,0.9] 10.23µm
D[v,0.1] 2.80µm
D[v,0.5] 5.89µm
Shape OFF

Source = :Sample
Focal length = 100 mm
Presentation = pil

Beam length = 5.0 mm
Log. Diff. = 3.253
Obscuration = 0.4153
Volume distribution

Model indp
Volume Conc. = 0.0161%
Sp.S.A 1.3317 m²/cc.

2 MICRON

Upper	In	Lower	Under	Upper	In	Lower	Under	Upper	In	Lower	Under
				57.7	0.0	49.8	100	9.82	12.0	8.47	41.8
				49.8	0.0	43.0	100	8.47	9.9	7.30	31.9
				43.0	0.0	37.0	99.9	7.30	9.7	6.30	22.2
				37.0	0.0	32.0	99.9	6.30	7.7	5.43	14.5
188	0.0	162	100	32.0	0.2	27.5	99.6	5.43	5.5	4.68	9.0
162	0.0	140	100	27.5	0.5	23.8	99.2	4.68	3.6	4.05	5.5
140	0.0	121	100	23.8	0.3	20.5	98.8	4.05	2.4	3.48	3.1
121	0.0	104	100	20.5	1.1	17.7	97.8	3.48	1.3	3.02	1.8
104	0.0	89.8	100	17.7	4.3	15.3	93.4	3.02	0.7	2.60	1.1
89.8	0.0	77.5	100	15.3	6.8	13.2	86.6	2.60	0.4	2.23	0.7
77.5	0.0	66.8	100	13.2	14.4	11.4	72.2	2.23	0.3	1.93	0.4
66.8	0.0	57.7	100	11.4	18.4	9.82	53.8	1.93	0.4	0.50	0.0

Sp
D[
D[3
D[v
D[v
D[v
Shap

Source = :Sample
Focal length = 100 mm
Presentation = pil

Beam length = 10.3 mm
Log. Diff. = 3.695
Obscuration = 0.5448
Volume distribution

Model indp
Volume Conc. = 0.0196%
Sp.S.A 0.7788 m²/cc.

5 MICRON

Upper	In	Lower	Under	Upper	In	Lower	Under	Upper	In	Lower	Under
				57.7	2.5	49.8	92.5	9.82	0.7	8.47	1.6
				49.8	6.0	43.0	86.5	8.47	0.4	7.30	1.2
				43.0	10.5	37.0	76.1	7.30	0.5	6.30	0.7
				37.0	14.2	32.0	61.8	6.30	0.4	5.43	0.3
188	0.0	162	100	32.0	17.2	27.5	44.6	5.43	0.2	4.68	0.1
162	0.0	140	100	27.5	15.4	23.8	29.2	4.68	0.1	4.05	0.0
140	0.0	121	100	23.8	9.5	20.5	19.7	4.05	0.0	3.48	0.0
121	0.0	104	100	20.5	5.8	17.7	13.9	3.48	0.0	3.02	0.0
104	0.5	89.8	99.5	17.7	4.3	15.3	9.5	3.02	0.0	2.60	0.0
89.8	1.1	77.5	98.4	15.3	3.2	13.2	6.4	2.60	0.0	2.23	0.0
77.5	1.5	66.8	96.9	13.2	2.5	11.4	3.8	2.23	0.0	1.93	0.0
66.8	1.8	57.7	95.0	11.4	1.6	9.82	2.2	1.93	0.0	0.50	0.0

Span 1.07
D[4,3] 30.90µm
D[3,2] 24.92µm
D[v,0.9] 46.46µm
D[v,0.1] 15.55µm
D[v,0.5] 28.79µm
Shape OFF

Source = :Sample
Focal length = 100 mm
Presentation = pil

Beam length = 10.0 mm
Log. Diff. = 4.922
Obscuration = 0.2947
Volume distribution

Model indp
Volume Conc. = 0.0291%
Sp.S.A 0.2408 m²/cc.

20 MICRON

Upper	In	Lower	Under	Upper	In	Lower	Under	Upper	In	Lower	Under
				57.7	0.7	49.8	98.0	9.82	9.5	8.47	36.0
				49.8	1.1	43.0	96.9	8.47	8.4	7.30	27.6
				43.0	1.7	37.0	95.2	7.30	8.1	6.30	19.5
				37.0	2.5	32.0	92.7	6.30	6.1	5.43	13.4
188	0.0	162	100	32.0	3.2	27.5	89.6	5.43	4.3	4.68	9.1
162	0.0	140	100	27.5	3.2	23.8	86.4	4.68	3.1	4.05	6.0
140	0.0	121	100	23.8	2.9	20.5	83.4	4.05	2.4	3.48	3.6
121	0.1	104	99.9	20.5	2.9	17.7	80.5	3.48	1.6	3.02	2.1
104	0.1	89.8	99.8	17.7	4.9	15.3	75.6	3.02	0.9	2.60	1.2
89.8	0.2	77.5	99.6	15.3	6.5	13.2	69.1	2.60	0.5	2.23	0.7
77.5	0.3	66.8	99.3	13.2	10.7	11.4	58.4	2.23	0.3	1.93	0.4
66.8	0.5	57.7	98.7	11.4	12.9	9.82	45.4	1.93	0.4	0.50	0.0

Sp
D[
D[
D[
D[
D[
Shap

Source = :Sample
Focal length = 100 mm
Presentation = pil

Beam length = 10.3 mm
Log. Diff. = 3.267
Obscuration = 0.4830
Volume distribution

Model indp
Volume Conc. = 0.0183%
Sp.S.A 0.6995 m²/cc.

TRI-MODAL

FIGURE 9a: Calibration:2600HSD:Data Analysis Results

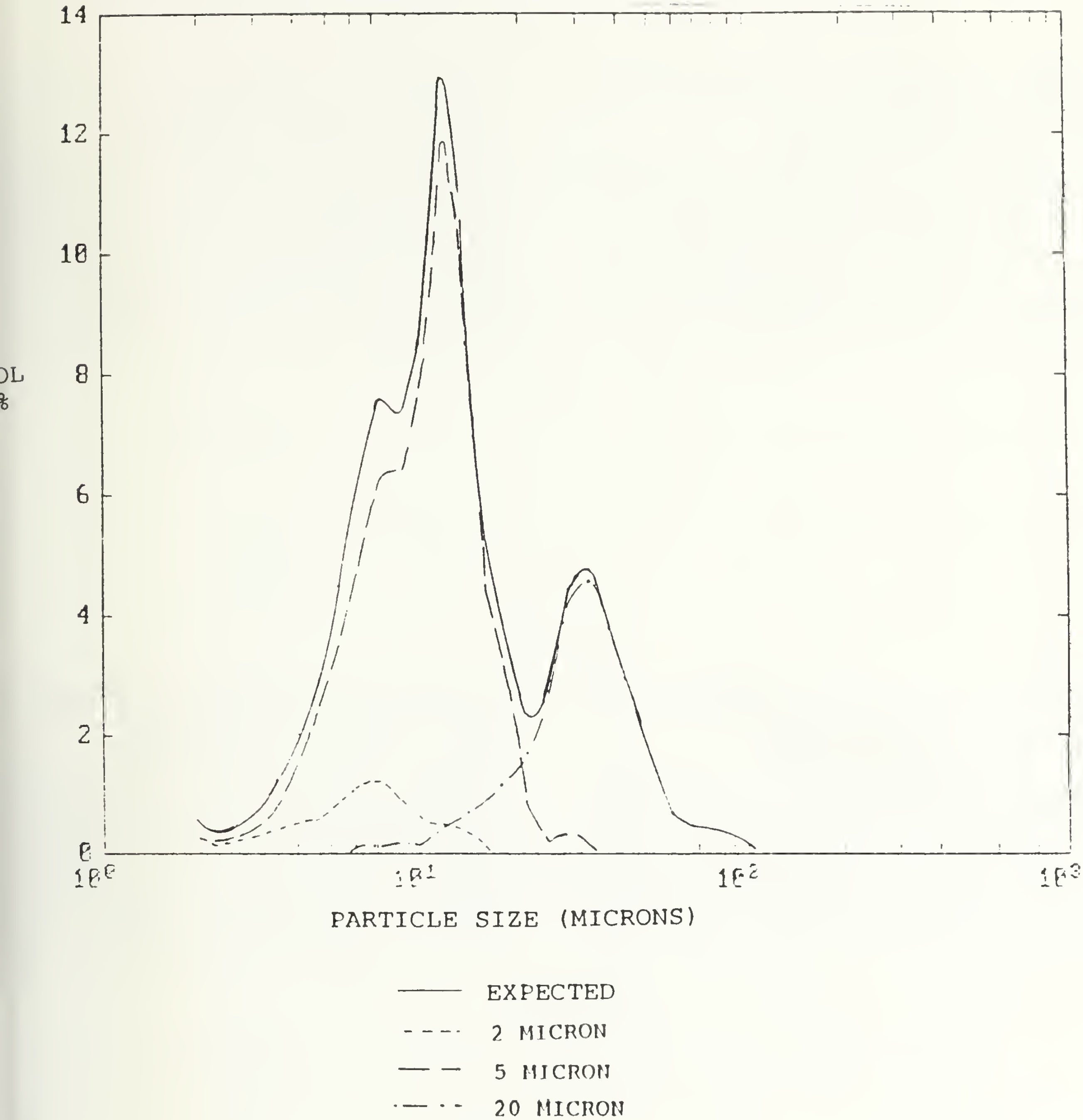


FIGURE 9b: Calibration:2600HSD:"Expected" Distribution

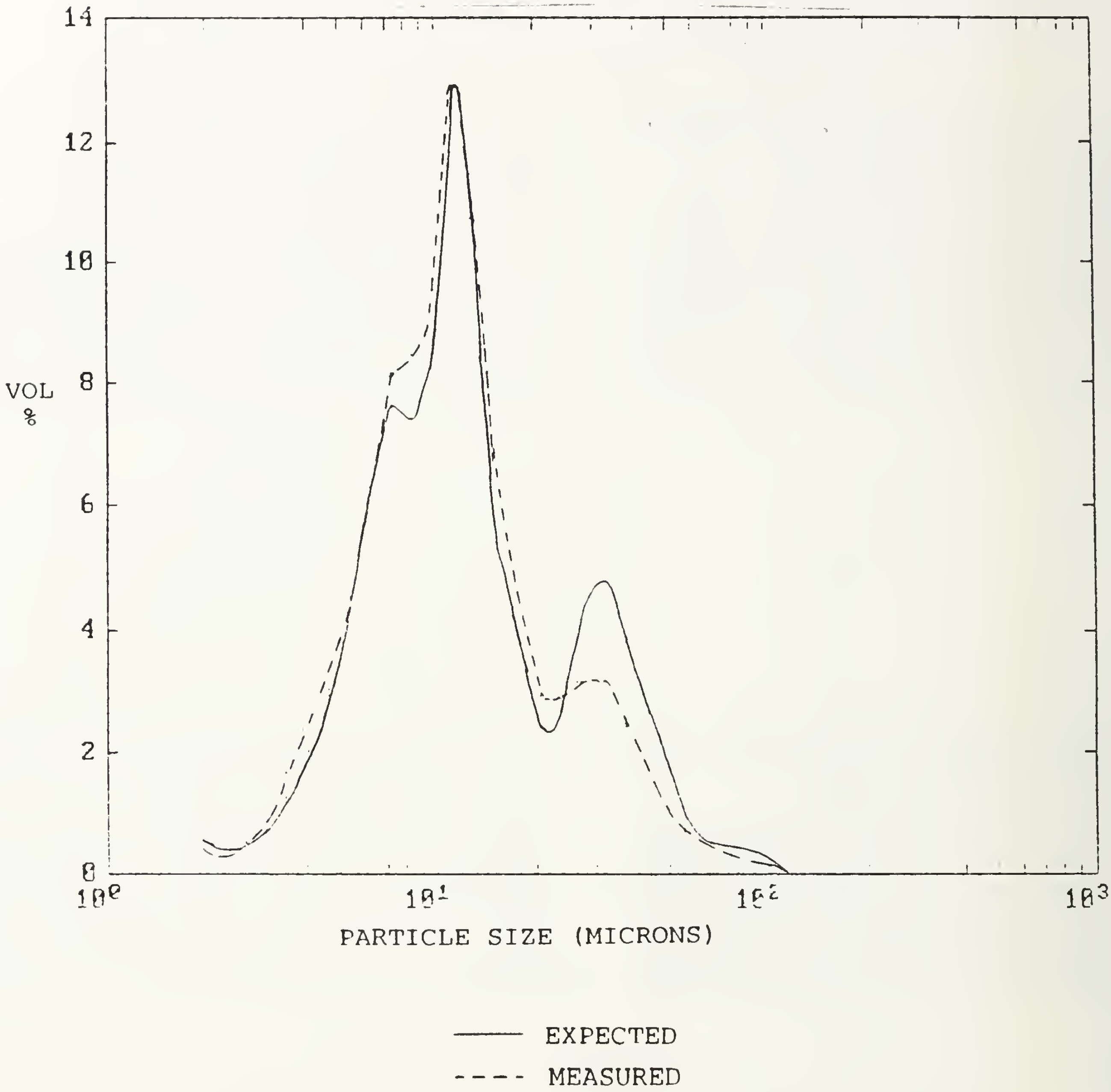


FIGURE 10: Calibration:2600HSD:"Expected" vs. Measured

	in	Lower	Under	Upper	in	Lower	Under	Upper	in	Lower	Under
				39.1	0.4	32.3	99.3	3.95	7.9	3.27	14.1
				32.3	0.6	26.7	98.7	3.27	5.5	2.70	8.6
				26.7	1.1	22.0	97.6	2.70	3.2	2.23	5.4
				22.0	1.8	18.2	95.8	2.23	1.9	1.84	3.5
	0.0	149	100	18.2	3.0	15.1	92.8	1.84	1.3	1.52	2.2
	0.0	123	100	15.1	4.8	12.4	88.0	1.52	0.9	1.26	1.3
	0.0	102	100	12.4	7.0	10.3	81.0	1.26	0.5	1.04	0.8
	0.0	83.9	100	10.3	9.4	8.48	71.6	1.04	0.3	0.86	0.5
	0.0	69.3	100	8.48	12.3	7.01	59.3	0.86	0.2	0.71	0.4
	0.0	57.3	100	7.01	13.8	5.79	45.5	0.71	0.1	0.59	0.2
	0.1	47.3	99.9	5.79	13.1	4.79	32.4	0.59	0.1	0.48	0.1
	0.2	39.1	93.7	4.79	10.3	3.95	22.0	0.48	0.1	0.20	0.0

= :Sample
length = 100 mm
tation = 1403

Beam length = 5.0 mm
Residual = 0.931 %
Obscuration = 0.3112
Volume distribution

Model indp
Volume Conc. = 0.0107%
Sp.S.A 1.2253 m^2/cc.

Span 1.70
D[4,3] 7.50µm
D[3,2] 4.90µm
D[v,0.9] 13.34µm
D[v,0.1] 2.86µm
D[v,0.5] 6.16µm
Shape OFF

2 MICRON

Upper	in	Lower	Under	Upper	in	Lower	Under	Upper	in	Lower	Under
				39.1	0.8	32.3	98.1	3.95	2.5	3.27	4.0
				32.3	1.3	26.7	96.8	3.27	1.4	2.70	2.7
				26.7	2.3	22.0	94.5	2.70	1.1	2.23	1.6
				22.0	4.2	18.2	90.3	2.23	0.6	1.84	1.0
180	0.0	149	100	18.2	7.2	15.1	83.1	1.84	0.4	1.52	0.5
149	0.0	123	100	15.1	11.6	12.4	71.5	1.52	0.2	1.26	0.3
123	0.0	102	100	12.4	15.6	10.3	55.9	1.26	0.1	1.04	0.2
102	0.0	83.9	99.9	10.3	16.4	8.48	39.5	1.04	0.1	0.86	0.1
83.9	0.1	69.3	99.8	8.48	14.0	7.01	25.6	0.86	0.0	0.71	0.1
69.3	0.2	57.3	99.7	7.01	9.5	5.79	16.1	0.71	0.0	0.59	0.0
57.3	0.3	47.3	99.4	5.79	6.1	4.79	10.0	0.59	0.0	0.48	0.0
47.3	0.5	39.1	98.9	4.79	3.4	3.95	6.6	0.48	0.0	0.20	0.0

Source = :Sample
Focal length = 100 mm
Presentation = 1403

Beam length = 10.6 mm
Residual = 0.292 %
Obscuration = 0.4026
Volume distribution

Model indp
Volume Conc. = 0.0116%
Sp.S.A 0.7657 m^2/cc.

Span 1.38
D[4,3] 11.08µm
D[3,2] 7.84µm
D[v,0.9] 18.04µm
D[v,0.1] 4.78µm
D[v,0.5] 9.59µm
Shape OFF

5 MICRON

	in	Lower	Under	Upper	in	Lower	Under	Upper	in	Lower	Under
				39.1	12.3	32.3	74.8	3.95	0.3	3.27	0.5
				32.3	18.1	26.7	56.7	3.27	0.2	2.70	0.3
				26.7	19.9	22.0	36.7	2.70	0.2	2.23	0.2
				22.0	15.9	18.2	20.9	2.23	0.1	1.84	0.1
	0.1	149	99.9	18.2	9.7	15.1	11.2	1.84	0.1	1.52	0.0
	0.0	123	99.9	15.1	4.9	12.4	6.3	1.52	0.0	1.26	0.0
	0.1	102	99.8	12.4	2.4	10.3	3.9	1.26	0.0	1.04	0.0
	0.2	83.9	99.6	10.3	1.2	8.48	2.7	1.04	0.0	0.86	0.0
	0.5	69.3	99.0	8.48	0.7	7.01	2.0	0.86	0.0	0.71	0.0
	1.4	57.3	97.6	7.01	0.5	5.79	1.5	0.71	0.0	0.59	0.0
	3.3	47.3	94.3	5.79	0.4	4.79	1.1	0.59	0.0	0.48	0.0
	7.2	39.1	87.1	4.79	0.3	3.95	0.8	0.48	0.0	0.20	0.0

= :Sample
ength = 100 mm
ation = 1403

Beam length = 10.0 mm
Residual = 0.687 %
Obscuration = 0.1469
Volume distribution

Model indp
Volume Conc. = 0.0106%
Sp.S.A 0.2850 m^2/cc.

Span 1.09
D[4,3] 27.11µm
D[3,2] 21.05µm
D[v,0.9] 41.83µm
D[v,0.1] 14.46µm
D[v,0.5] 25.05µm
Shape OFF

20 MICRON

Upper	in	Lower	Under	Upper	in	Lower	Under	Upper	in	Lower	Under
				39.1	2.4	32.3	95.0	3.95	3.0	3.27	5.0
				32.3	3.6	26.7	91.4	3.27	1.9	2.70	3.0
				26.7	5.1	22.0	86.2	2.70	1.1	2.23	1.9
				22.0	6.9	18.2	79.3	2.23	0.6	1.84	1.3
180	0.0	149	100	18.2	8.7	15.1	70.6	1.84	0.5	1.52	0.8
149	0.0	123	100	15.1	10.2	12.4	60.4	1.52	0.3	1.26	0.5
123	0.0	102	100	12.4	11.1	10.3	49.2	1.26	0.2	1.04	0.3
102	0.0	83.9	100	10.3	11.2	8.48	38.0	1.04	0.1	0.86	0.2
83.9	0.1	69.3	99.9	8.48	10.2	7.01	27.8	0.86	0.1	0.71	0.2
69.3	0.3	57.3	99.6	7.01	8.7	5.79	19.0	0.71	0.1	0.59	0.1
57.3	0.7	47.3	98.8	5.79	6.5	4.79	12.5	0.59	0.1	0.48	0.0
47.3	1.5	39.1	97.4	4.79	4.5	3.95	8.0	0.48	0.0	0.20	0.0

Source = :Sample
Focal length = 100 mm
Presentation = 1403

Beam length = 10.6 mm
Residual = 0.948 %
Obscuration = 0.3759
Volume distribution

Model indp
Volume Conc. = 0.0106%
Sp.S.A 0.7611 m^2/cc.

Span 2.00
D[4,3] 13.11µm
D[3,2] 7.88µm
D[v,0.9] 25.21µm
D[v,0.1] 4.35µm
D[v,0.5] 10.41µm
Shape OFF

TRI-MODAL

FIGURE 11a:Calibration:MS:Data Analysis Results

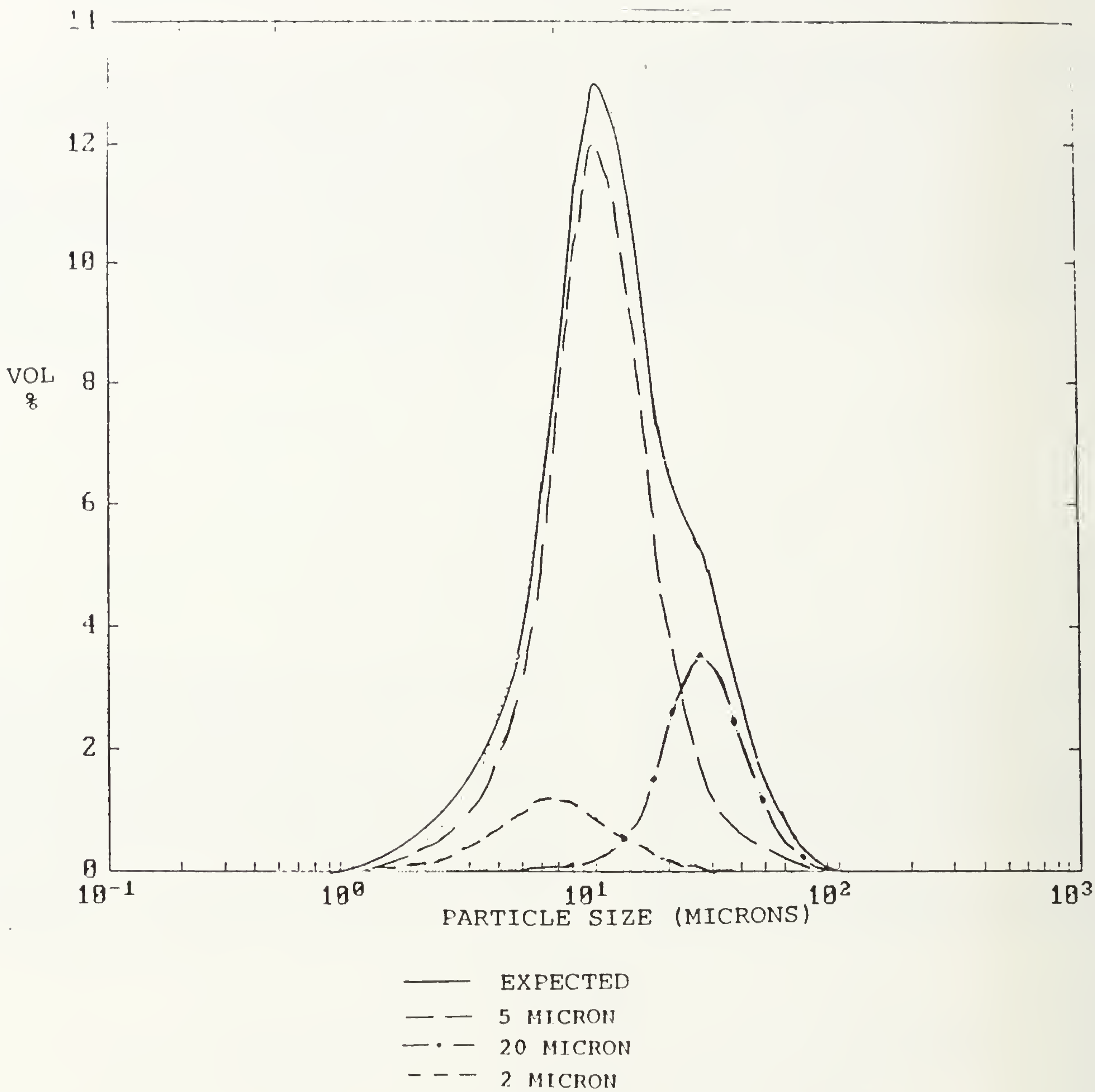


FIGURE 11b:Calibration:MS:"Expected" Distribution

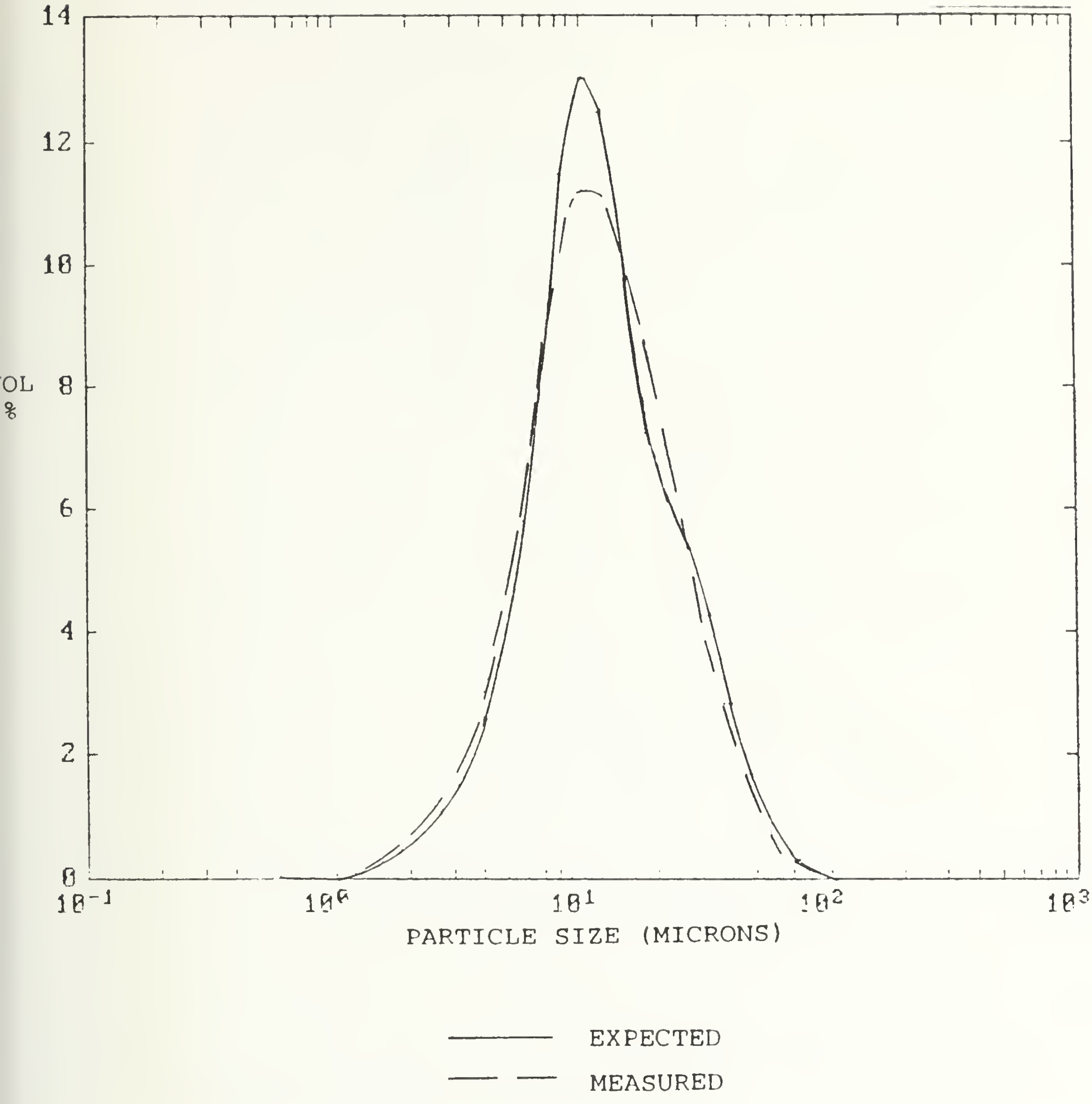


FIGURE 12: Calibration:MS:"Expected" vs. Measured

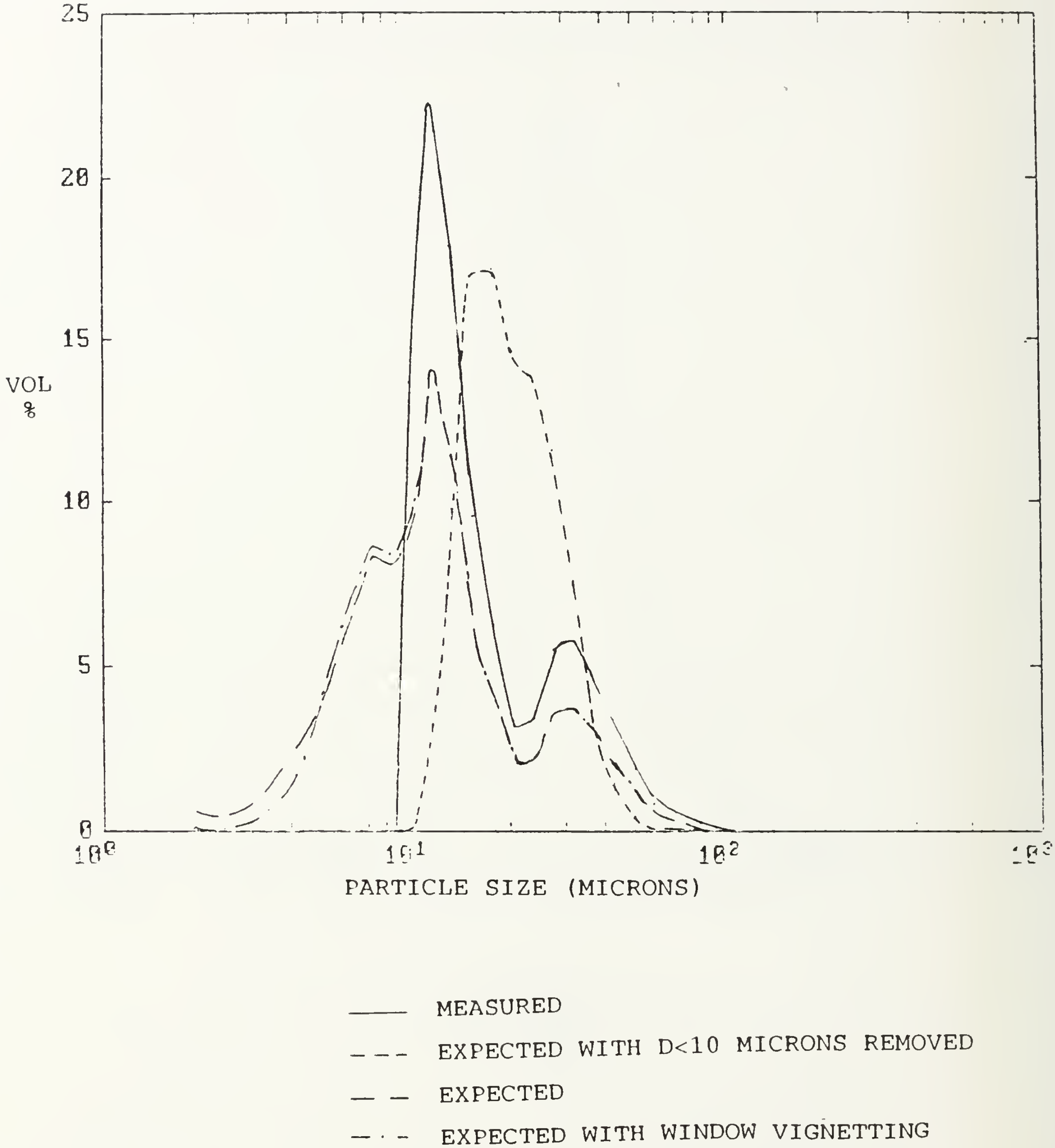


FIGURE 13: Malvern Measurements in the Motor

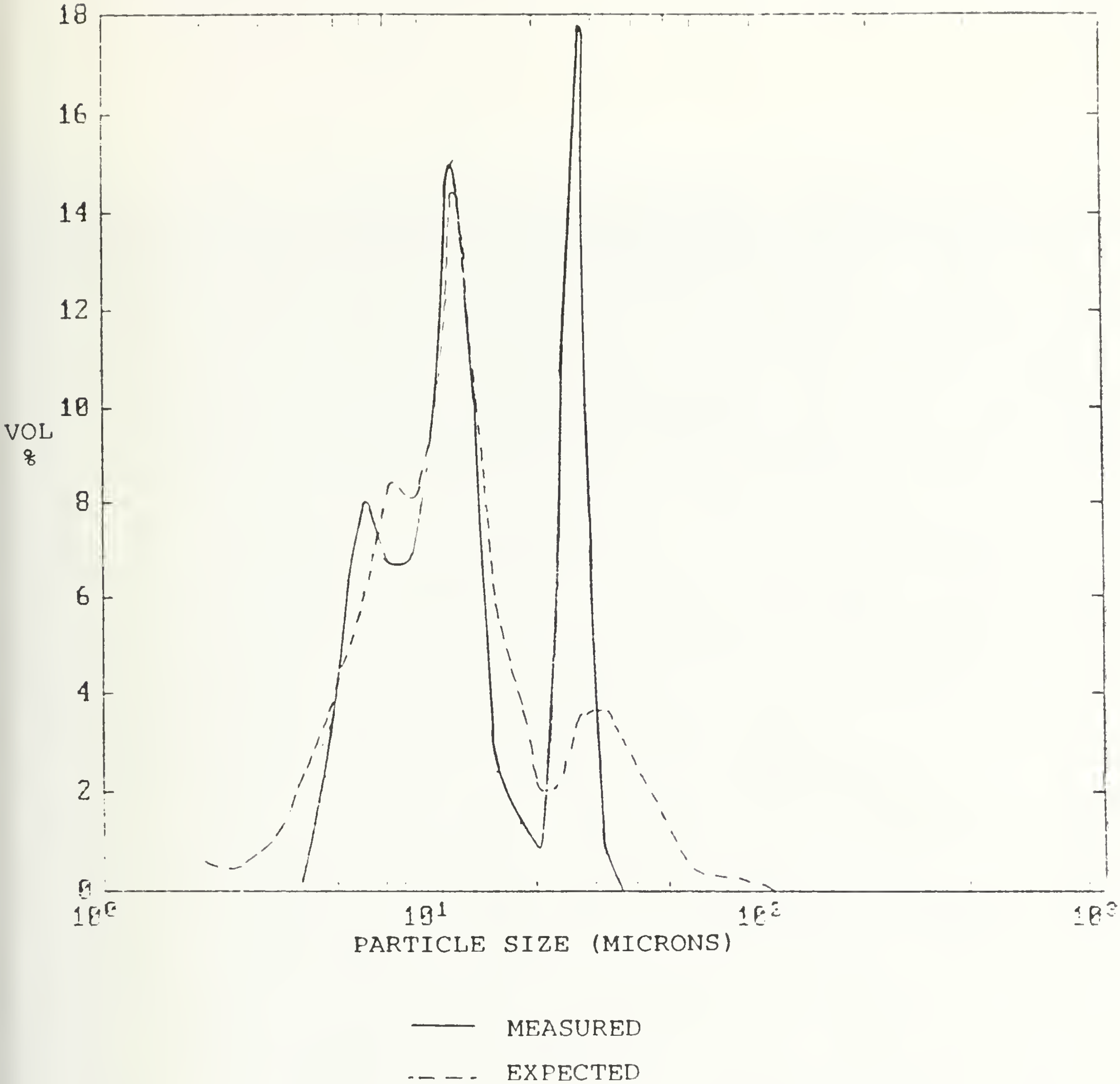


FIGURE 14: Malvern Measurements in the Plume

FIGURE 15: PDPA Results: Centerline

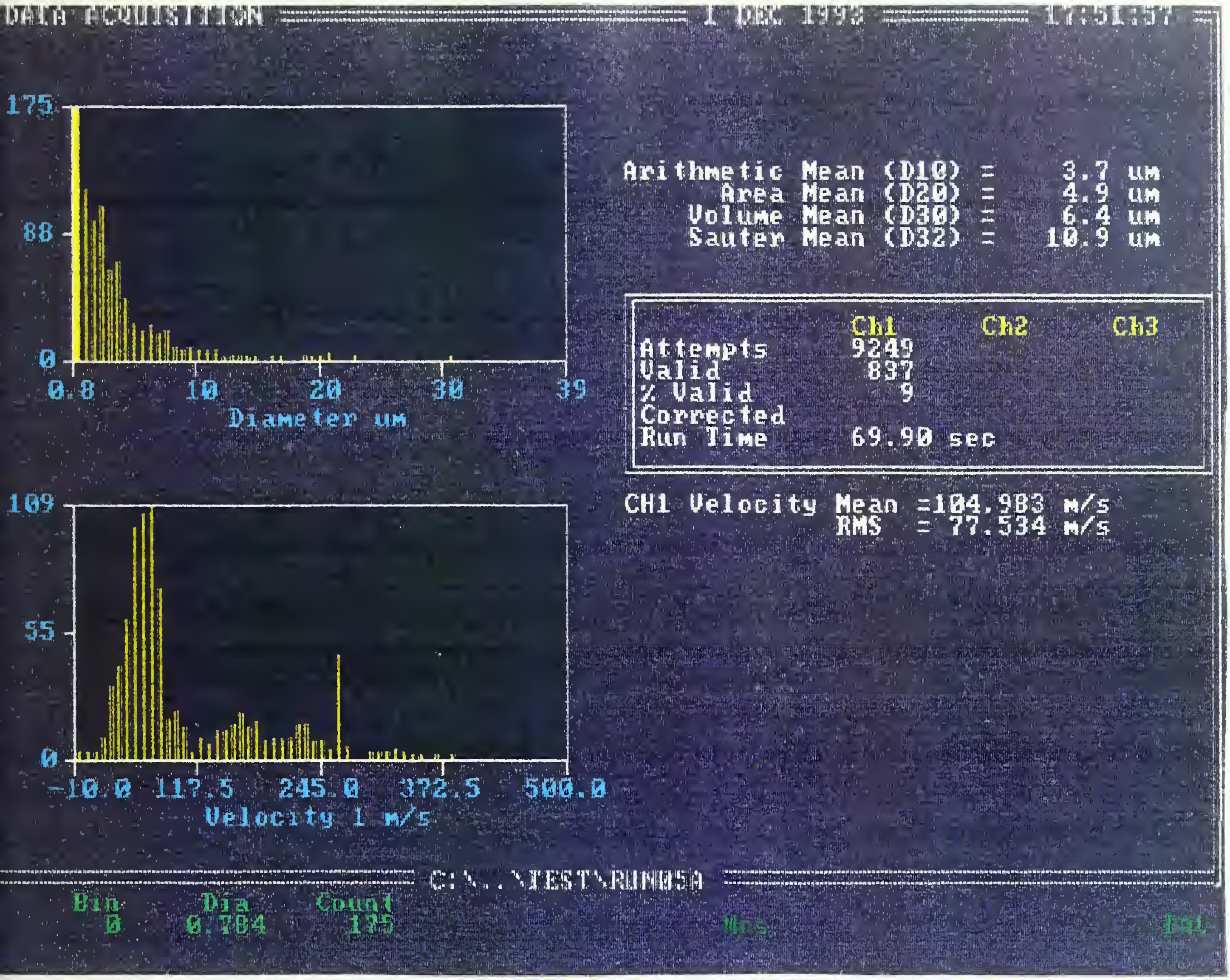
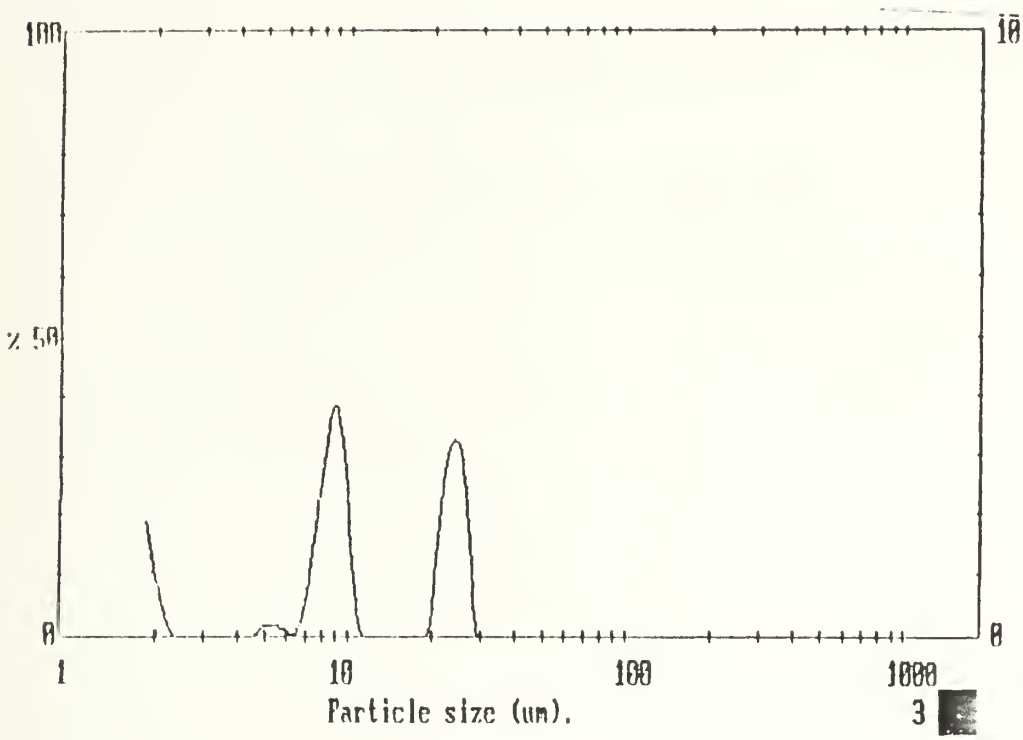


FIGURE 16: PDPA Results: Radially Spaced



Upper	in	Lower	Under	Upper	in	Lower	Under	Upper	in	Lower	Under
				57.7	0.0	49.8	100	9.82	7.2	8.47	80.1
				49.8	0.0	43.0	100	8.47	4.9	7.30	75.2
				43.0	0.0	37.0	100	7.30	0.7	6.30	74.5
				37.0	0.0	32.0	100	6.30	0.2	5.43	74.2
188	0.0	162	100	32.0	0.2	27.5	99.8	5.43	0.3	4.68	73.9
162	0.0	140	100	27.5	5.3	23.8	94.5	4.68	0.0	4.05	73.9
140	0.0	121	100	23.8	5.4	20.5	89.0	4.05	0.0	3.48	73.9
121	0.0	104	100	20.5	0.3	17.7	88.8	3.48	0.0	3.02	73.9
104	0.0	89.8	100	17.7	0.0	15.3	88.8	3.02	0.0	2.60	73.9
89.8	0.0	77.5	100	15.3	0.0	13.2	88.8	2.60	0.1	2.23	73.8
77.5	0.0	66.8	100	13.2	0.0	11.4	88.8	2.23	1.4	1.93	72.4
66.8	0.0	57.7	100	11.4	1.5	9.82	87.3	1.93	72.4	0.50	0.0

Source = Data:Input Focal length = 100 mm Presentation = pia	Beam length = 50.0 mm Log. Diff. = 3.651 Obscuration = 0.3347 Volume distribution	Model indp [4, 0] Volume Conc. = 0.0004% Sp.S.A 4.5951 m²/cc.

Span	16.66
D[4,3]	4.70µm
D[3,2]	1.31µm
D[v,0.9]	21.33µm
D[v,0.1]	0.70µm
D[v,0.5]	1.24µm
Shape OFF	

FIGURE 17: Malvern Data For PDPA [Ref. 11]

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